EARTHQUAKE EPICENTERS AND STRUCTURE OF THE PACIFIC REGION OF NORTH AMERICA (SOUTHERN PART)

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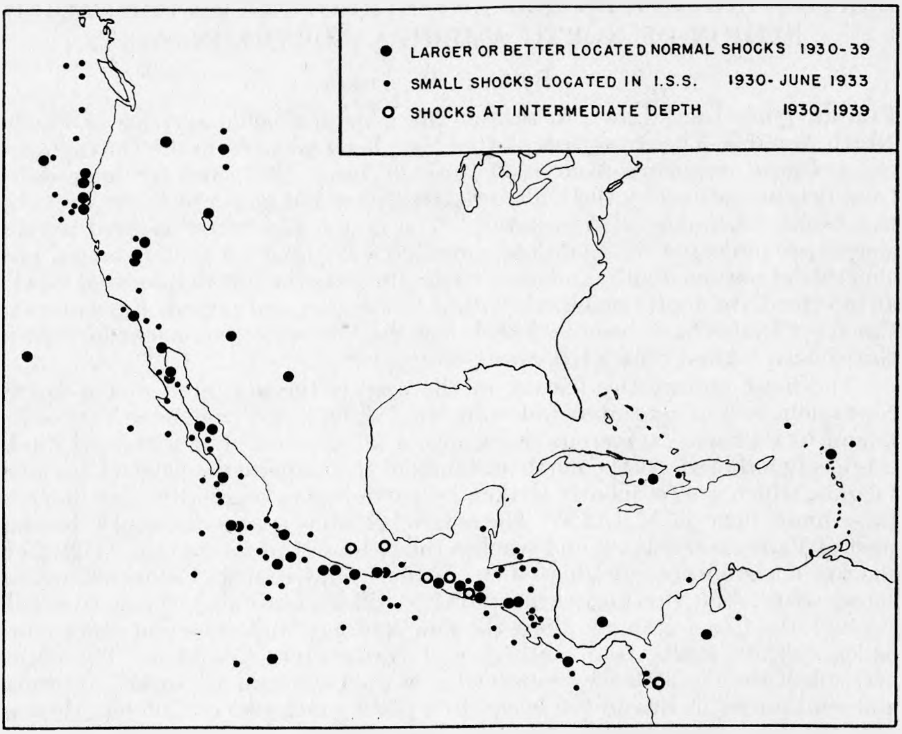
Figure 1 has been drawn to exhibit the general seismic activity of Pacific North America. The epicenters plotted have been taken from the *International Seismological Summary* from 1930 through June, 1933, and for later dates from determinations by the United States Coast and Geodetic Survey and by the Jesuit Seismological Association. The larger and better located normal shocks are indicated by solid dots; small dots are used for minor shocks, presumably of normal depth; and open circles indicate the few well-located shocks at intermediate depth which fall within this region and period. Epicenters in the West Indies have been included, but the few scattered shocks located in the eastern United States have been omitted.

The most noteworthy feature of the map is the appearance of a nearly continuous belt of epicenters following the Pacific Coast from near Vancouver Island to Panama. Numerous shocks occur off this belt, but within its limits it is easily followed. At the northern limits of the map are the Queen Charlotte Islands, which are frequently shaken by earthquakes originating just beyond these limits near 53°N, 132°W. The active belt runs nearly due south, passing west of Vancouver Island, and reaches the coast of California near 41°N. Few shocks of significance originated in northern and central California within these years; but the historical record justifies continuing the active belt through the Coast Ranges, along the San Andreas fault zone and other more or less parallel faults, into southern and southeastern California. The major active belt then follows the eastern edge of the peninsula of Lower California, and continues this line in the ocean to a point southwest of Colima, Mexico, near the northern end of the Acapulco Deep. Here it turns eastward, reaching the coast in the state of Oaxaca, and continuing through the coastal region of Guatemala, Salvador, Nicaragua, and Costa Rica to Panama. In Guatemala and Nicaragua the normal shocks are accompanied by "intermediate" shocks, at depths of about 100 to 150 km.

The important structural loop through the West Indies is much less active than the Pacific Coast, so that the seismological data have little bearing on the geological problems of the exact location and character of this loop. The history of occasional strong earthquakes in the Antilles and in Venezuela and Colombia supports the hypothesis that the loop forms part of the Pacific group of structures. Considering the known geology, it is probable that the western end of the loop appears in the normal shocks on the Mexican coast near Colima, and that it continues eastward through central Mexico, where our map shows two epicenters associated with shocks at depths of 100 km.

In the territory of the United States occasional large shocks occur far inland from the Pacific Coast. Some of these are in the Cordilleran region, such as those shown on the map in Montana (1935) and Texas (1931); still more belong to the Great Basin province, as is shown by several shocks mapped in Nevada. The shock near Salt Lake City (1934) might be considered as belonging to either of these groups.

Off the north coast of California certain epicenters lie farther west than the main active line. (Cf. the preceding paper by Professor Byerly.) Near the western edge of the map appears the extraordinarily isolated epicenter of the earthquake of January 4, 1933, at 28°.5′N, 127°.0′W. Although this was not a large shock, the observations are adequate to insure reasonable accuracy of

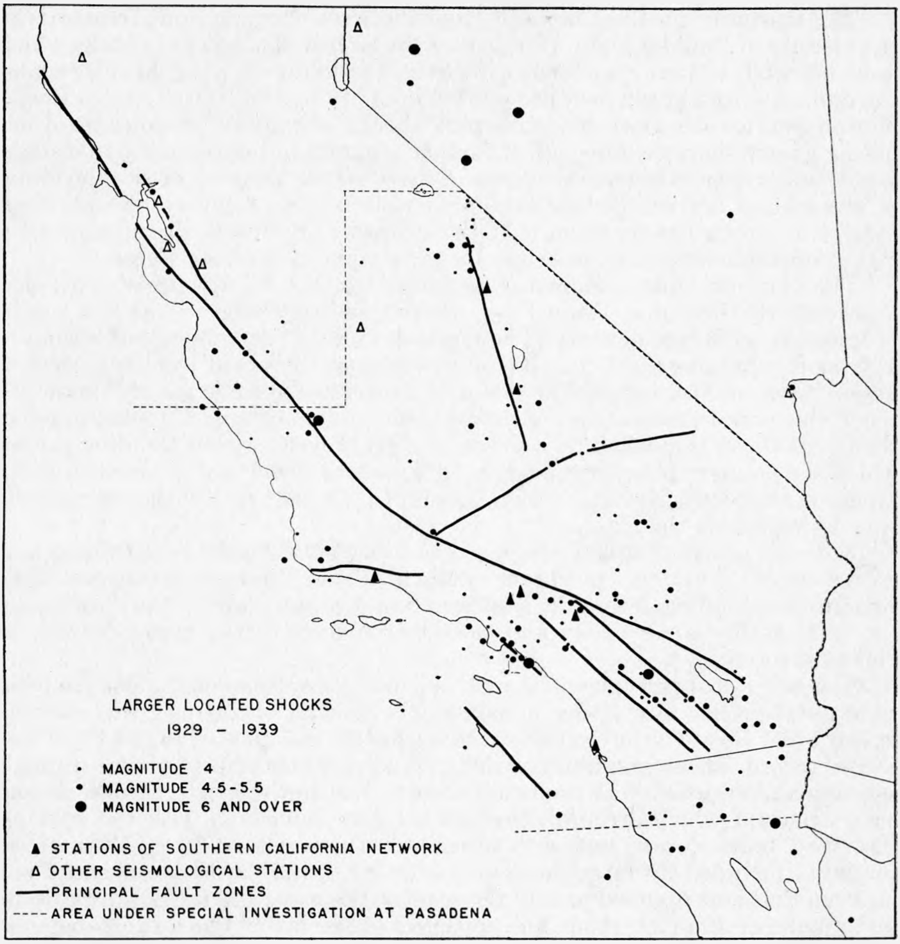


the location. This is a true Pacific shock; the edge of the continental shelf is comparatively close to the coast of California. The shocks south of Mexico near 10° N, 104° W, are also presumably oceanic; the largest of them, on May 28, 1936, is very reliably located.

Figure 2 exhibits the larger recent activity of the southern California area. The location and equipment of the seven stations in southern California makes the cataloguing complete for all but the smallest shocks within the area outlined by the dashed boundary; in this area the map shows all epicenters of shocks instrumentally located since 1929, for which the magnitude on the scale used at Pasadena is 4 or greater. This scale is logarithmic in the instrumentally recorded amplitudes at a standard distance, so that an increase of one unit in the magnitude means that the recorded amplitudes are larger by a factor of 10. Shocks of magnitude 4.5 or greater are found to be capable of causing damage in a settled area; shocks of magnitude 6 and greater are potentially destructive.

The listing of these shocks in the region studied is complete except for omissions due to instrumental failures or other accidents, from January 1, 1934, to April 30, 1939. Other shocks from 1929 to 1933 have been added from incomplete lists. Shocks outside the dashed line have been indicated so far as data were available, except that no attempt has been made to show shocks in the region of San Francisco Bay or northward, these being covered in Professor Byerly's paper.

The most important active faults are shown. The San Andreas fault zone appears as the principal seismic axis of the region, and several other important faults branch from it. The figure shows clearly the remarkable lack of relation between the geographical distribution of activity and the major faults. This is



not in any way due to error in instrumental determination of the epicenters; shocks of these magnitudes can usually be located within a few kilometers, and the instrumental locations are often supported by macroseismic data.

Inspection of the figure shows that epicenters tend to cluster in certain small areas. Several of the areas include each a major fault, and some of the epicenters lie on or close to it; but others clearly do not, and often these can be placed definitely on some of the minor faults which occur almost everywhere in the region.

The San Andreas fault appears surprisingly inactive, particularly in the most closely observable segment, which lies nearest to the stations at Pasadena, Mount Wilson, and Riverside. This segment bears unmistakable evidence of very recent activity and was almost certainly in action during the major earthquake of January 9, 1857.

The clustering of epicenters in the neighborhood of Los Angeles and Pasadena is not due to the location of the Pasadena station, as shocks of the magnitude mapped cannot escape notice anywhere in the entire area. Some of these points—specifically, those along the Inglewood fault near the coast—are due to the Long Beach earthquake of 1933 and its aftershocks.

The epicenter on the Colorado River between Nevada and Arizona is in the vicinity of Boulder Dam. It indicates the largest of a series of shocks which have been felt in that region subsequent to the filling of Lake Mead, behind the dam. A seismograph installed at Boulder City by the United States Reclamation Service has recorded numerous shocks of various magnitudes originating a very short distance off. A further program of instrumental investigation is under way. Although evidence of inactivity in the area before the filling of the lake is not completely satisfactory, it is reasonably convincing, and there is a strong presumption that these shocks are due to disturbance of a rather unstable crustal equilibrium by the weight of the lake water.

The Garlock fault is shown branching from the San Andreas zone in a northeasterly direction. Tejon Pass, where this branching occurs, is a region of frequent moderate activity. The Garlock fault is very important structurally, as it separates the Great Basin province on the north from the Mojave Desert area on the south. The latter is an area of comparatively moderate relief, the mountainous areas consisting of old and much eroded rocks; whereas the Great Basin is marked by a series of roughly north-south trending ranges which are younger physiographically. The westernmost and greatest of these ranges is the Sierra Nevada, which is bounded on the east by the Sierra fault zone indicated on the map.

Note the nearly complete absence of activity between the San Andreas and Sierra zones. The few epicenters north of Tejon Pass are associated with structures extending across the southern San Joaquin Valley. North of these, the area of the Great Valley and the western slope of the Sierra Nevada is almost inactive.

Absence of mapped epicenters west of Tejon Pass, between the San Andreas zone and the coast, may be due in part to the difficulty of getting good locations in this area. However, no considerable seismicity is indicated here by the historical record; although an important geological discontinuity passes through the area and various minor faults are known. Just to the south, various shocks have occurred which are probably not directly connected with the curving east-west fault shown, but with other structures related to it. With these should be included the large shock of November 4, 1927, with an epicenter not far from that here mapped just off the coast to the west, and the Santa Barbara earthquake of June 29, 1925. The epicenter of the latter was a short distance west of Santa Barbara, which is indicated on the map as the site of one of our stations.

The activity of the Mojave Desert block shows a peculiar distribution in time, which will be discussed below.

All the known northwest-southeast faults of the southern area are active, but with a very irregular distribution along their length. The continuation of these faults into Mexico has not been indicated, but the seismicity continues across the international boundary. The epicenter near the head of the Gulf of California has been a site of great activity; large shocks originated there on December 30 and December 31, 1934.

The historical information on seismic activity in California, particularly southern California, is decidedly inadequate. No records of any kind are available earlier than 1769. Three major earthquakes are known to have occurred in California: (1) that of January 9, 1857, which was associated with large displacements along the San Andreas fault, centering apparently near Tejon Pass, and extending possibly 150 km. in both directions; (2) that of March 26, 1872, in the major Sierra fault zone—the displacements observed at the surface were not, however, on the Sierra fault, which bounds the Sierra Nevada block, but on a parallel group of faults 10 to 20 km. farther east, at the edge of Owens Valley; and (3) the "San Francisco earthquake" of April 18, 1906, with observed displacements along about 200 km. of the San Andreas fault, and activity, and displacements along either the same or a parallel fault, extending another 180 km. to the north. A major earthquake also occurred in central Nevada on October 2, 1915, and a somewhat smaller one in west-central Nevada on December 20, 1932.

The segments of the San Andreas fault affected by the earthquakes of 1857 and 1906 have been comparatively quiescent in recent years. The late Maxwell W. Allen pointed out that the imperfect historical record also indicates very little activity along these segments, small to moderately strong shocks being reported more frequently from the rest of the fault zone. He suggested a division of the fault zone into segments where the rocks are strong and fracture only under great stress, occasioning major earthquakes, and segments where they are weaker, yielding more readily and occasioning less violent shocks.

Figure 3, at the end of this paper, represents recent activity in a limited area near the central stations of the group. Besides the faults drawn in the other figures, several important minor faults are shown. The four maps include all the located shocks of all magnitudes during four six-month periods, from January to June, inclusive, of 1932, 1934, 1936, and 1938. The very small shocks of magnitude 2.5 and less are marked with the smallest sized dots; location for them is less certain than for the others, and some may be artificial. These shocks were given more attention in 1932 than subsequently, which accounts for the somewhat larger number of them shown for that year.

The figure shows the Mojave Desert shocks previously referred to. Up to 1929, the instrumental records, which are very imperfect as compared to those now being obtained, show few, if any, shocks which are likely to have occurred in this area. Recognizable activity commenced with a shock of magnitude 5 on September 26, 1929; after this, shocks from several epicenters in the area occurred with increasing frequency up to the end of 1932. Some of these appear on the 1932 map. On December 20, 1932, a major earthquake occurred in Nevada; thereafter the Mojave shocks practically ceased. In 1938 activity in this region resumed; two shocks of the group appear on the 1938 map. Activity has continued into the present year (1939). It is natural to suppose some dynamic connection between these shocks and the major strain released in Nevada; however, this is the only known possibility of the kind in this region.

The phenomena of the Long Beach earthquake of 1933 are clearly shown. The 1932 map shows shocks along the northern end of the Inglewood fault and near Catalina Island, but none on the southern segment of the Inglewood fault; however, small shocks of the Long Beach group show peculiarities which were not recognized until after the principal shock, and some of these may have escaped location in the first half of 1932. The 1934 map shows epicenters along and near that segment of the Inglewood fault which was active in the 1933 earthquake; finally, the 1936 map shows returning activity along the northern end of the fault, as well as continuing aftershocks along the southern segment. These shocks have continued.

The comparative inactivity of the San Andreas fault is conspicuous on these maps. So, also, is the regional distribution of activity. The only faults outlined by epicenters are the Inglewood fault, in consequence of the aftershocks just mentioned, and the San Jacinto fault, trending off the southeast corner of the map.

Routine location of epicenters at Pasadena is based on travel-time charts constructed by Gutenberg from a study of the large shocks of 1929, 1930, and 1931. These charts are based on a "granitic" layer (velocity of longitudinal waves, 5.55 km/sec.) with a thickness of about 14 km., the earthquake foci lying in the lower part of this layer at depths scattering about 12 km. Several intermediate layers intervene between this and the base of the continental crustal layers, which is nearly 40 km. deep. The corresponding travel times fit the observations very well for the region lying north and east of Pasadena, where granitic rocks are exposed or are overlain by comparatively small thicknesses of sedimentary and metamorphic rocks. To the northwest, westl and south the sedimentary structures are thicker and more complicated, and the standard travel times provide only a good first approximation. Occasiona, shocks appear to have focal depths of near 25 km.; these have been found especially in the coastal area southwest of Los Angeles and Pasadena. No shocks have been found for which the data even suggest abnormally great focal depths such as occur in other parts of the world.

As a sample of the statistics, it may be mentioned that between 200 and 250 shocks of magnitude 3 and over occuring within the dashed-line boundary of figure 2, are recorded each year.

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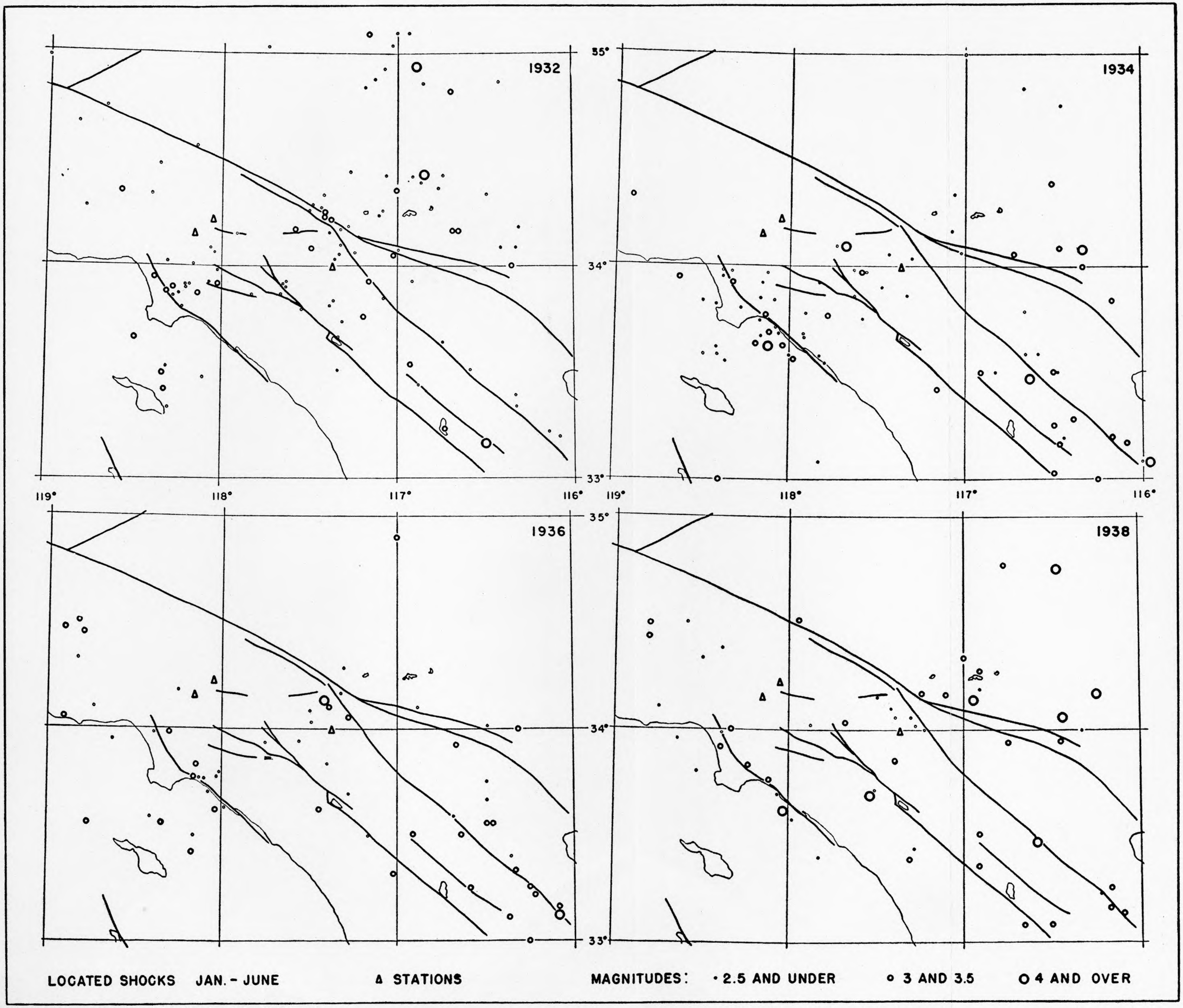

FIGURE 3.—Earthquake epicenters of a limited area near the central stations of the southern California group, for four six-month periods, January–June, 1932, 1934, 1936 and 1938.